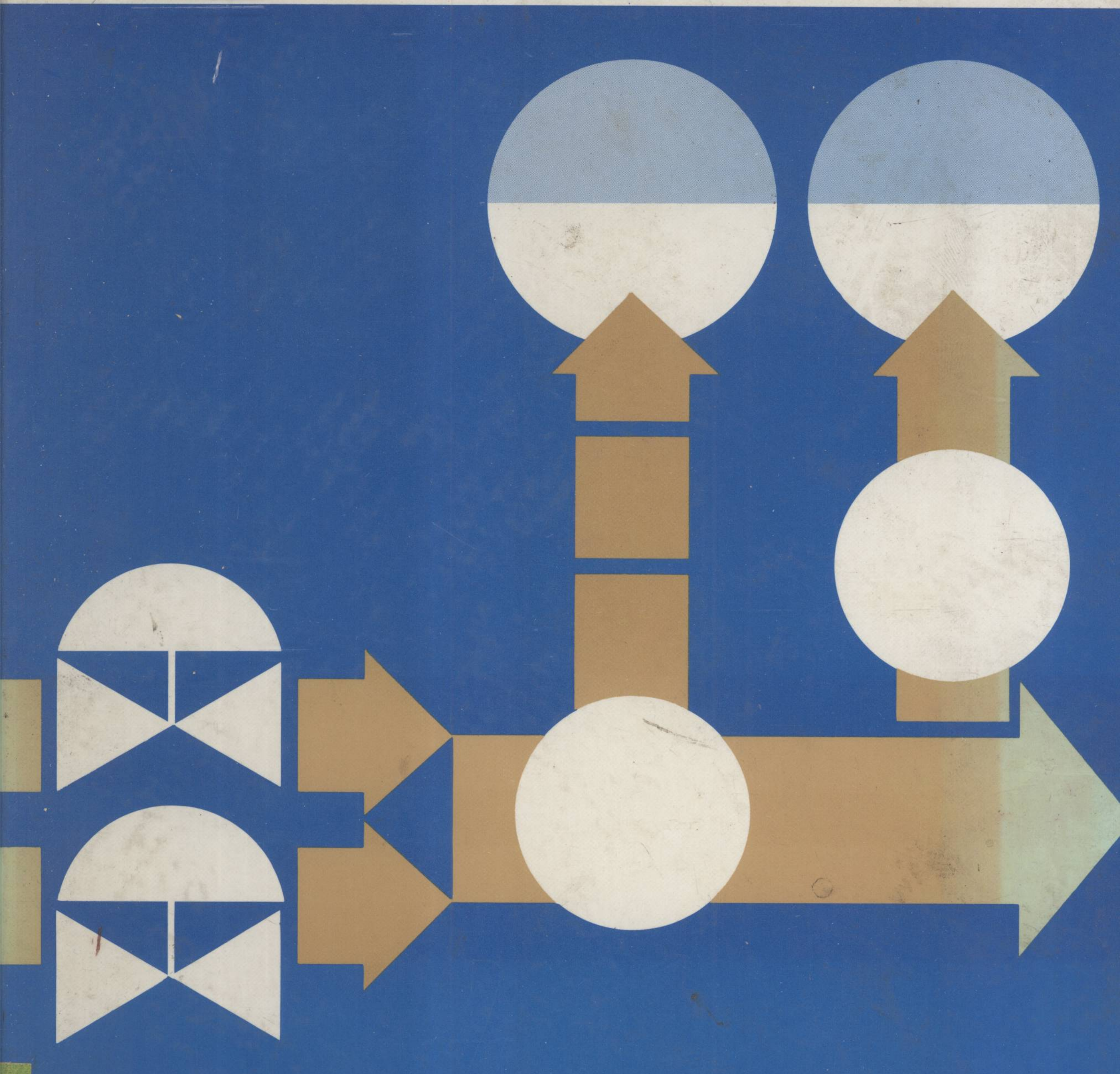
CONTROLLING MULTIVARIABLE PROCESSES

by F.G. Shinskey



An Independent Learning Module from the Instrument Society of America

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Preface

ISA's Independent Learning Modules

This is an Independent Learning Module (ILM) on *Controlling Multivariable Processes;* it is part of the ISA Series of Modules on Control Principles and Techniques.

Comments about This Volume

This ILM on *Controlling Multivariable Processes* is intended to guide the reader in the procedures which are essential in applying controls to modern industrial processes. Many of the procedures are mathematical in nature—unavoidably so, in that the resulting systems are implementations of mathematical solutions. Yet most of the procedures involve simple algebra, with partial differentiation being the most demanding discipline.

The course is intended for engineers who are responsible or will be responsible for control-system application and design. A fundamental understanding of feedback control is an essential prerequisite; the ILM on *Fundamentals of Process Control Theory* will be helpful in this regard. Engineers having a process background will find this module easier to follow than those without because system designs are based on mathematical relationships that describe the process to be controlled. Nonetheless the presentation, examples, and exercises will be helpful to all who wish to develop skills in control-system design.

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Unit 1:
Introduction

UNIT 1

Introduction

Welcome to ISA's Independent Learning Module *Controlling Multivariable Processes*. This first unit presents the general control problem for the process plant, its multivariable nature, and the need for coordinating these variables.

Learning Objectives — When you have completed this unit, you should:

A. Understand the multivariable nature of production processes.

B. Be able to classify the variables into broad groups.

C. Appreciate the need for coordinating their controls into a system structure.

1-1. Process Inputs and Outputs

Any process may be represented as a block, with variables both entering and leaving. The input variables are acted upon by the process to develop the output variables as in Fig. 1-1. Input variables are typically rates of flow in a continuous process, or quantities in a batch process. These streams may be either entering or leaving the process—stream direction does not determine the flow of information. (Observe that flow out of a vessel affects its inventory to the same degree as inflow.) Some input variables are capable of independent manipulation by an operator or by a controller—these are called *manipulated* variables. The remaining input variables, which cannot be independently manipulated, are considered to be *disturbing* variables.
Often these are the output variables from other processes, in which case they may be either controlled or uncontrolled. Disturbing variables may also include the conditions surrounding the process, such as ambient temperature.

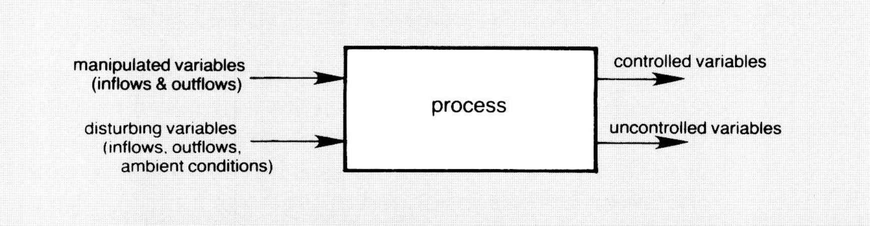

Fig. 1-1. Process inputs and outputs are designated on the basis of information flow.

Process output variables are considered either *controlled* or *uncontrolled*. Control is achieved through manipulation, so that each variable that is controlled requires the manipulation of a process input. Output variables that are uncontrolled simply may not be influenced by any of the manipulable inputs. Also, the number of output variables exceeding the number of manipulated input variables must remain uncontrolled.

The combination of a single controlled variable and a single manipulated variable is considered a single-loop process, regardless of the number of disturbing and uncontrolled variables present. There are many familiar single-loop processes—controlling room temperature with a steam valve and controlling the pH of a waste stream by adding reagent are two of the more common examples.

1-2. Multiple Controlled Variables

Even the simplest of production processes requires the control of *two* variables—product rate and quality. An example of a process with two controlled variables would be the blending of two streams to form a mixture as in Fig. 1-2. Product flow must satisfy certain market demands in the long term and productivity goals in the short term. Secondly, the composition of the mixture must meet some specification in order to satisfy the use for which it is intended. If multiple specifications must be met, additional product-quality control loops must be added to the basic two-variable system.

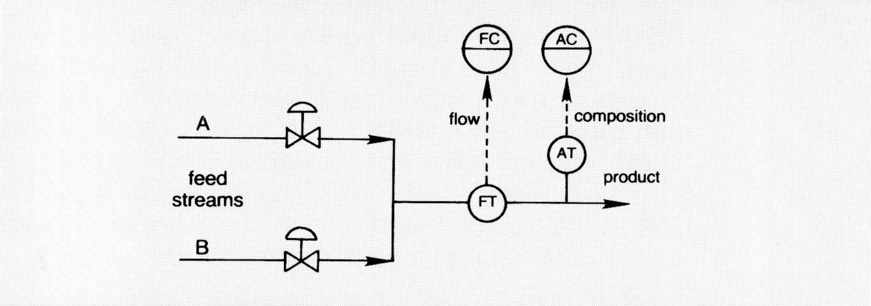

Fig. 1-2. The two-stream blender is perhaps the simplest multivariable process.

Usually a feedstock must pass through a series of stage-wise operations in its conversion into a finished product. Control may be required at each stage to obtain certain desired characteristics in the product. Most processes have storage vessels located between these sequenced operations to give a degree of dynamic isolation between them. This practice adds loops for inventory control, even when the storage volumes are minimal.

Separation processes split a feed stream into two or more products, each of which may require quality control. These processes are driven by a flow of energy whose balance must be maintained. This is the type of operation common to oil refineries, where a crude feedstock containing many components is separated into many products with fewer components.

Modern processing plants have both series and parallel operations interconnected by flow networks that can become quite complex. As a consequence, virtually every process encountered by the control engineer is multivariable in nature. While his knowledge of single-loop control is essential in applying controls to these processes, it is by no means sufficient.

1-3. Types of Controlled Variables

The types of processes encountered in the industrial world are too many to be meaningfully classified. But, as a beginning, the controlled variables themselves may be readily classified, giving an insight into their role and importance in the process, and identifying the means commonly used to measure them. Table 1-1 lists five categories of controlled variables, along with the measurements that usually identify them. Because most of the measurements appear more than once in the table, an understanding of their roles in the functioning of the process is vital to success of the control system. For example, an environmental temperature-control loop contributes a different function to the process than an inventory temperature-control loop. Hence, it may operate differently and be subject to different forces. Each category is examined in detail in a later unit, but at this point they are introduced for purposes of distinction.

Variable type	Measurement
1. Production rate	Flow
2. Inventory	
a. Gas	Pressure
b. Liquid	Liquid level or pressure
c. Solid	Weight
d. Composition	Chemical analysis
e. Energy	Temperature or pressure
3. Environmental	
a. Temperature	Temperature
b. Pressure	Pressure
c. Composition	Chemical analysis
4. Product quality	
a. Physical	Physical property
b. Chemical	Chemical analysis
5. Economic	Flow, flow ratio, valve position, chemical analysis

Table 1-1. Classification of Controlled Variables

The production-rate variable determines the rate at which a process operates. There is generally only one of these in any given process. It is usually the rate of feed, but in some cases it may be the rate of flow of a final or intermediate product. When operations are conducted in series, a single production rate sets the steady-state throughput of all operations. Production rate is a disturbing variable to all processes because it affects all other controlled variables.

Inventory variables represent the accumulation of material or energy at specific points in the process. In the steady state, inventory must remain constant (this defines the steady state); hence, inventory controllers are responsible for closing material and energy balances. But a steady state can be maintained at *any* level of inventory. Therefore, one issue that will be discussed in Unit 3 is the choice of an appropriate inventory level.

Environmental variables determine the conditions under which a process functions. They are particularly important in conducting chemical reactions, which are sensitive to all three dimensions —temperature, pressure, and composition. Room temperature is an environmental variable affecting the process of people at work. Environmental variables tend to affect process performance as much as product quality.

Product quality needs to be controlled in every process. It is perhaps the most important controlled variable because product value depends on it. It is the most difficult to control because it is disturbed by almost every other variable in the process. It also is difficult to measure in most cases, usually requiring sampling and even off-line determinations, whose delays degrade control.

The last group of controlled variables is economic in nature, and in fact, these are rarely controlled. They represent the cost of production, which is usually not obtainable in a single measurement. Occasionally, losses are measurable as the flow of a costly agent or premium fuel needed for control, or as the concentration of valuable product in a waste stream. Economic controls are being added to conserve energy and other resources, but only after product-quality goals have been satisfied.

Example 1-1

Classify the controlled variables represented by the transmitted signals from the process in Fig. 1-3, into the five categories given in Table 1-1.

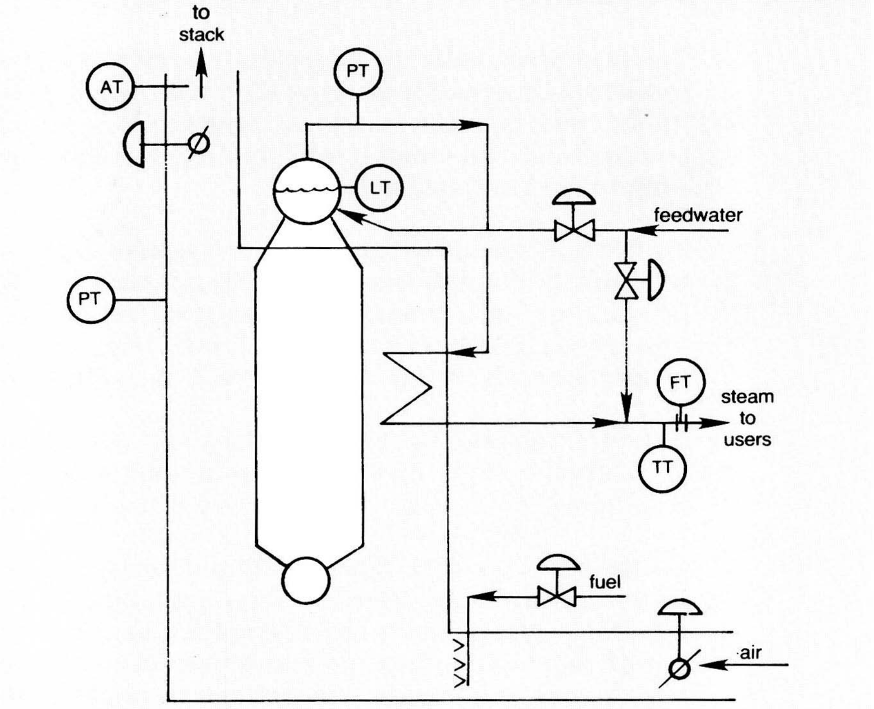

Fig. 1-3. A superheated steam boiler features each of the five classes of controlled variables.

1. Production rate is steam flow, usually determined by demands placed on the steam header by users. In this illustration it is an uncontrolled variable or controlled elsewhere.

2. Inventory of liquid is drum level—as much feedwater must be supplied as steam is boiled away to keep liquid inventory constant.

   Inventory of energy is steam pressure—heat removed in the steam must be supplied by the combustion of fuel.

3. The environmental variable is furnace pressure or draft, which is controlled to maintain efficient and safe firing.

4. Product quality is the temperature of the superheated steam.

5. The economic variable in this example is the composition of the flue gas, as this determines how much energy is lost to the stack.

1-4. Process Interactions

The principal challenge in designing control systems for industrial processes is arriving at a structure which minimizes the interactions between variables. If interactions were absent, control would be unnecessary. As it is, interactions always are present, and to varying degrees.

Production rate influences all other variables, because production requires the coordination of many resources into the product. As production rate increases, the rates of all resources entering the process, i.e. feedstocks, solvents, fuels, work, etc., must increase proportionately if product quality is to be maintained.

If production rate is changed unilaterally, quality and inventory variables tend to be upset first. The actions of their controllers in responding to the disturbance in turn disturb other variables.

Consider the boiler of Fig. 1-3. Should the user of steam increase its withdrawal rate, steam pressure and temperature will begin to fall almost immediately due to a reduction in energy inventory. Liquid level will follow. To return pressure to its control point, fuel flow must increase. This has two secondary effects—liquid level will fall faster as the rate of boiling increases, and the flue gas will become rich in unburned fuel if air flow is not increased. Adjusting air flow can correct the oxygen-deficient condition, but this action upsets furnace pressure.

The existence of process interactions poses two problems to the control-systems engineer:

1. With most processes it is impossible to connect pairs of manipulated and controlled variables into single loops that will not interact. However, there is usually a "best" pairing for any given process, and determining this pairing is essential to achieving steady-state stability in the process.

2. Interaction tends to be so pervasive that even the "best" configuration of single loops is a compromise that may fail to give acceptable dynamic performance. In most cases then, substantial improvement can be gained by coordinating the variables in relationship to their natural interaction within the process.

The magnitude of the system-design problem varies factorially with the number of manipulated variables. (The case in which there is an equal number of controlled and manipulated variables is clear, because that is also the number of possible independent single loops.) Where there are only two manipulated and two controlled variables, as in Fig. 1-2, there are only two possible configurations of single loops: Valve A can be used to control variable 1 and valve B variable 2, or valve A can control variable 2 and valve B variable 1. The engineer can usually make the best assignment intuitively. For the system in Fig. 1-2, he would rightly manipulate the larger stream to control flow, and the smaller to control composition.

However, the choice is not alway obvious, and occasionally the wrong pairing is chosen. But in this 2×2 case, the problem is easily corrected by exchanging the connections—there are only two possible configurations, and if one is unsatisfactory, the other must be better.

The problem quickly explodes in size as more variables are added. A typical distillation column has five manipulated variables, offering the possibility of 120 different configurations of five single loops. Many of these configurations will have one or more loops that are intuitively ineffective and therefore can be eliminated from consideration. Yet many possibilities remain, and the optimum selection is far from obvious. In fact, it is only through careful analysis of the process interactions that the optimum configuration can be found. Even then, certain equipment constraints may preclude implementation of the optimum, and a suboptimum configuration may have to be accepted.

An examination of the boiler in Fig. 1-3 illustrates the ineffectiveness of single-loop controls in coping with interaction. Flue-gas oxygen content, for example, is affected equally by fuel and air. Therefore it is not only foolish but dangerous to manipulate them independently. The most effective control systems will then not be a simple arrangement of single loops, but will be a coordinated structure, whose interactions mirror the relationships which naturally exist in the controlled process. Increases in process performance and efficiency are bought at the cost of increasing complexity in the control-system structure.

1-5. Process Knowledge

The need for inter-loop coordination adds another dimension to the system-design problem. The number of possible coordinated configurations becomes a multiple of the factorial number for single-loop configurations. The probability of selecting the optimum configuration diminishes rapidly as the number of variables increases. Furthermore, the likelihood is not much greater of changing an inadequate configuration into a successful